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FOREWORD

The study reported herein constitutes a part of the research program on low-density gas dynamics conducted by the Mechanical Engineering Department of the University of Tennessee for the United States Air Force under Contract No. 40(600)-922. This is the report on Research Task No. 1 of this contract.

The contributions of Mr. C. F. Fisher and Mr. H. J. Wilkerson of the Mechanical Engineering Faculty are gratefully acknowledged.

ABSTRACT

A complete literature survey has been made in order to establish the current state of wind tunnel diffuser technology. Special attention has been given to low-density hypervelocity applications. Such important flow parameters as geometry, boundary layer flow, real gas effects and rarefied gas effects have been discussed. A series of experimental tests have been recommended which would yield results applicable to predicting diffuser performance in the low-density hypervelocity range.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

~~C. D.~~ Reifsteck	Jean A. Jack
Colonel, USAF	Colonel, USAF
DCS/Plans	DCS/Test

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A	Cross-sectional area
A^*	Sonic cross-sectional area
C_p	Specific heat
f	Body force
h	Semi-height of flow passage
J	Enthalpy plus kinetic energy
k	Thermal conductivity
l	Characteristic dimension
l'	Mean free path
M	Mach number
M_x	Mach number at which a shock occurs
N_{Ku}	Knudsen number
N_{Pr}	Prandtl number
N_{Re}	Reynolds number
P	Static pressure
$P_{t.s.}$	Static pressure in test section
P_y	Static pressure downstream of shock
P_o	Stagnation pressure
P_{o_x}	Stagnation pressure upstream of shock
P_{o_y}	Stagnation pressure downstream of shock
$P_{o_{t.s.}}$	Stagnation pressure in test section

$P_{t,e,}$	Diffuser exit total pressure
P_t	Stagnation pressure in test section (measured by pitot tube)
T_o	Stagnation temperature
T_∞	Reference temperature
t	Time
t_o	Reference time
u	Velocity
u_∞	Reference velocity
X	Coordinate
γ	Ratio of specific heats
η	Efficiency, $P_t/P_{t,e} = (P_t/P_{t,s})^{1-\eta}$
μ	Dynamic viscosity
ν	Kinematic viscosity
δ^*	Boundary layer displacement thickness $\frac{1}{\rho_\infty u_\infty}\int_0^\delta (\rho_\infty u_\infty - \rho u)\,dy$
ρ	Density
ρ_∞	Reference density

1.0 INTRODUCTION

With the advent of outer atmosphere explorations, the need to experimentally test vehicles and propulsion systems under simulated flight conditions has become a pressing engineering problem. Although our knowledge of the earth's atmosphere is limited, we have sufficient data to approximate the density, temperature, pressure, etc. for a given altitude. It is the simulation of these atmospheric properties and vehicle velocities which confronts our foremost aerodynamic testing centers at this time.

Many new engineering problems have resulted from our desire to accomplish this task. In order to simulate the required conditions as shown by the shaded area in Figure 1, it is necessary to resort to very high stagnation pressures and temperatures. The required stagnation conditions are indicated in Figure 1. This type of simulation has been accomplished to a certain extent in "now operating" testing facilities; however, the majority of these facilities have very short run times. It is desirable to develope new facilities which will have continuous operation in the required flight simulation range.

One of the uncertainties associated with continuous wind tunnel operation is that of diffuser performance. In the range of flight simulation for outer atmosphere applications, test section static pressures are very low and the required stagnation pressures high. The extent of pumping capacity required to obtain and maintain these conditions is determined in part by the pressure recovery which may be accomplished with a diffuser downstream of the test section.

The objectives of this study were to establish the current state-of-the-art on wind tunnel diffusers, to determine the parameters of importance to diffuser performance, and to recommend experimental tests which might be conducted in existing facilities to predict the performance of diffusers in more advanced wind tunnels.

To accomplish these objectives, a large portion of this study was devoted to an extensive search of the pertinent technical literature and to an attempt to accumulate all existing information on the subject into a complete resume. Part 2 is a review of the current state-of-the-art on wind tunnel diffusers and includes performance data for typical existing facilities. Part 3 is a brief study of the important parameters associated with diffuser performance. As one would expect, Reynolds number is the most critical parameter for this range of diffuser applications. Part 4 outlines experimental tests which could be performed on existing facilities in order to predict the performance of future diffusers.

Figures 2 and 3 are included to show the Mach number and Reynolds number ranges of interest. The Reynolds numbers are based on a characteristic dimension of unity. The shaded areas indicate the regions of interest.

2.0 STATE-OF-THE-ART

An attempt has been made to determine the present state of wind tunnel diffuser technology. Approximately 2000 technical abstracts were reviewed and the 90 references listed in the Bibliography were given thorough study. A brief review of both published and unpublished data relating to performance and design of wind tunnel diffusers is presented.

Many supersonic wind tunnels have diffusers designed primarily on the basis of subsonic experience, resulting in high overall pressure ratios for the tunnels and little pressure recovery in the diffusers. This low recovery is due to the fact that, aside from a normal shock, viscosity effects in the diffuser introduce additional losses, thus lowering the exit pressure. Since a diffuser employing a system of oblique shocks should have a better pressure recovery than one with a single normal shock, efforts were made to improve supersonic wind tunnels along these lines. Variable-area diffusers whose throats can be closed after flow has been established were of interest because of their higher pressure recovery.

Lukasiewicz (Ref. 64) and Wegener and Lobb (Ref. 66) presented very complete summaries of diffuser performance for entry Mach numbers up to 10. Wegener and Lobb obtained pressure recovery data for diffuser entry Mach numbers between 5.9 and 9.6 for a two-dimensional, flat-plate, variable geometry diffuser. The Reynolds number per foot of length was approximately 9×10^7. From the test data, a diffuser with a single-peaked throat and a three-degree plane wall divergence aft of the throat was selected as most practical. The pressure recovery ratio for this optimum diffuser varied, depending on Mach number, from 1.8 to 2.3 times the recovery ratio for a pitot (or impact) tube operated at the test-section Mach number. It was found that the major part of the pressure recovery took place upstream of the throat and that viscous effects play an important role in this process. Since neither the parallel plate (constant area throat) nor the angle of the diverging section had any significant effect on the pressure recovery, it was concluded that the diffuser section after the throat may be kept short. It was also found that hypersonic tunnels may be started at pressure ratios about equal to the pitot pressure ratio, thus making additional starting devices unnecessary. The minimum diffuser throat area at which the shock system could be "swallowed" and supersonic flow could be established was only two-thirds of that predicted by one-dimensional theory in spite of the viscous effects present. The presence of models and supports increased the minimum diffuser throat somewhat but did not materially affect overall pressure ratios.

Lukasiewicz presented a review of the published data including the above work of Wegener and Lobb. Some observations made in this paper are summarized. Pressure recovery in diffusers without contraction is improved by use of a long constant-area entry but is always smaller than the theoretical normal shock (i.e., pitot tube) recovery. In general, the phenomenon of shock compression in constant-area ducts can be expected to depend on Mach number and Reynolds numbers based on tube diameter and boundary-layer thickness. At Mach numbers below 4, maximum contraction of constant geometry diffusers (or starting contraction of variable geometry diffusers) is closely predicted by simple theory. At optimum contractions (which are practically equal to maximum contractions), normal shock pressure recoveries are achieved, although appreciably larger starting pressure ratios are usually required at $M > 2$. It is preferable that the angles of two-dimensional contractions should be of the order of 3° to 4° at $M < 4$ and increase to about 9° at $M = 7$ to 10. With variable diffusers, optimum contraction increases with Mach number and is appreciably larger than starting contraction but smaller than maximum possible contraction. Contraction angles should be of the order of 5° at $M < 3$ and increase to 15° and more at $M = 7$ to 10. Lower stagnation pressure ratios appreciably smaller than the normal shock values are obtained at $M > 2$ and amount to only half the normal shock stagnation pressure ratio at $M \sim 7$. It was concluded that although the performance of variable diffusers deteriorates when models are mounted in the working section, it is advantageous to use this type diffuser in hypersonic tunnels.

The conclusions and observations made by both of these studies (Ref. 64 and 66) are based on $M < 10$ and $N_{Re} \sim 10^6$ with air as the working fluid. An investigation to study the effect of variable-geometry diffusers on the pressure-ratio requirements for diffusers operating at Mach numbers above 10 has been made by Johnston and Witcofski (Ref. 55). The tests were conducted at a Mach number of approximately 20 in a 3-inch-diameter helium tunnel having a conical nozzle and equipped with two-dimensional variable geometry diffusers. The diffuser entrance wall length varied from 8.81 inches to 20.50 inches. The Reynolds number per foot of length was $\sim 10^7$. The overall pressure ratio required to maintain supersonic flow, with a constant area diffuser, was reduced 34 percent by utilizing the optimum area ratio (~ 0.45) and the shortest entrance wall tested (8.81 in.). The effect of supersonic-diffuser entrance wall angle was investigated and the optimum was found to be approximately 4.75° for the 8.81 inch entrance wall length. For these tests at $M = 20$ in helium, only about 61 percent of the test-section pitot pressure is recovered. The small variations in Reynolds number which were effected in these tests had no significant influence on the overall pressure ratios.

Henshall and Zlotnick (Ref. 9) report that Professor Schaaf's (University of California, Berkeley) experience showed that only 30 or 40 percent pressure recovery over test section static pressure was available at M = 3-4 for tests in their low-density tunnel. Professor Maslack (Ref. 72) has briefly described the diffuser as a simple truncated concial shell mounted approximately two feet downstream of the nozzle exit and concentric with the nozzle axis. The small diameter of the truncated cone was approximately equal to the exit diameter of the nozzle. The pressure recovery quoted was achieved with no model or pressure measuring probe in the stream. When a model was inserted into the test section, the cross-stream support sufficiently influenced the flow boundary so as to destroy the major portion of the pressure recovery. It was pointed out by Professor Maslach that this program had as its purpose stabilizing the flow conditions rather than obtaining a given pressure recovery.

The most extensive experimental investigation in the field of low-density wind tunnel diffusers has been reported by Potter et. al. (Ref. 38). In this investigation a total of 14 fixed-geometry diffusers were tested at a Mach number of 9.7 and Reynolds number of 2640 per foot. The ratio of boundary layer thickness to nozzle exit radius was approximately 0.85. The test section of this tunnel was of the open-jet type, having a nozzle exit diameter of 5.84 inches. The diffuser configurations were obtained from one entrance cone, one exit cone, and a series of central sections of varying diameters fabricated from sheet metal. The smallest diameter central section had the greatest axial length, and each succeeding configuration of equal minimum diameter was made by cutting off part of the center section. Each succeeding diffuser of larger throat diameter was made by cutting off part of the conical sections so that their smaller diameters matched the new central section. The effect of central section length was investigated with entrance and exit section lengths constant for any given throat diameter, but the conical pieces became successively shorter with each increase in throat diameter.

Detailed measurements of the reduction in overall pressure ratio were not presented, but in private communication with Potter (Ref. 89) additional information was obtained which permitted the data to be presented in the ordinary manner for diffusers. The lowest pressure recovery recorded was for the constant area 10-inch pipe and was equal to 0.048 times the pressure recovery of a pitot tube operated at the test section Mach number. The highest pressure recovery for the best configuration was equal to 0.24 times the pitot tube recovery. Other values varied between these two extremes. These data were obtained with no model or support in the test section. The variation of axial length of the constant area diffuser throats had negligible effect on diffuser performance. The diameter of the throat section was quite important. Free-jet length was an influencing factor in these tests, but it became less critical as the throat diameter was enlarged. The apparent optimum value for the area ratio of nozzle exit and diffuser throat was unity. When the throat diameter was increased beyond this apparent optimum, influence of the free-jet length became relatively unimportant.

A term frequently used to compare results from various diffusers is the efficiency η , which may be defined as

$$P_t/P_{t,e} = (P_t/P_{t,s})^{1-\eta}$$

where η is a measure of the deviation from isentropic compression. From Potter's data (Ref. 38 and 89) the performance of the diffuser has been estimated in terms of diffuser efficiency. A simple short-tube orifice 6 inches in diameter increased the efficiency from 16 percent to 23 percent over that for the 10 inch pipe test section. Addition of a convergent section further increased the efficiency to 33 percent. A finite length of constant area throat resulted in an improvement over the performance of a convergent cone-frustum alone.

The effect of blockage was investigated for one set of operating conditions. The ratio of model frontal area to cross-sectional area at nozzle exit minus area of displacement boundary layer was 0.08. This blockage decreased the efficiency from 33 to 26 percent for a 6-inch diffuser throat and from 24 to 12 percent for a 4.8-inch diffuser throat.

The extremes of the data presented by Potter are shown in Figure 4. Estimated diffuser efficiency is plotted as a function of free-jet length both for a 10 inch pipe and for the optimum convergent-constant area throat-divergent diffuser. The performance of all other configurations tested lies between these two extremes.

The diffuser exit total pressures obtained in several facilities (Ref. 55, 64 and 66) in terms of test-section pitot pressures are compared in Figure 5. The estimated values from Schaaf (Ref. 9 and 72) and Potter (Ref. 38 and 89) are also included in this plot. The optimum configuration from Potter's work is plotted. In Figure 6 the same performance information is presented in terms of diffuser efficiency. Because of the difference in the ratio of specific heats, the data for air and helium should not be compared directly. This is emphasized in Figure 6 by showing two theoretical curves computed for a normal shock compression.

Although most investigators agree that the effectiveness of a diffuser in a low-density wind tunnel may be marginal, it is believed that its use will be imperative in low-density, hypervelocity, continous operation.

3.0 FLOW PARAMETERS

For many complicated physical circumstances, engineering design information has been obtained primarily from experimentation. The complexity of the problem must be reduced to a minimum for the greatest economy in carrying out experiments, in correlating the results, and in using this information for design. This is done by reducing to a minimum the number of independent variables or parameters which must be considered. The design of a diffuser to operate in the flow regime defined in Part I is certainly a complex problem, and an attempt should be made to establish the important flow parameters. Experience shows that both analytical solutions and experimental correlations usually result in simpler relationships when the variables are treated in dimensionless groups (i. e., $M = u/a$, $N_{Re} = ul/\nu$, etc.) rather than separately.

Dimensional analysis proceeds from Buckingham's π theorem and is simply a formal method of combining variables into dimensionless groups. This procedure is carried out without considering the physical nature of the process in question and, in general, yields several sets of dimensionless quantities. The method attaches no physical significance to the results; therefore, the selection of the proper set of results must be based upon other considerations.

Another method has come into use which avoids some of the ambiguities of dimensional analysis. This method, sometimes called "similitude" or "differential similarity," is based upon physical reasoning. After determining the parameters which indicate similarity between processes, it is necessary to establish the relative importance of these parameters for specific applications.

3.1 SIMILITUDE

This technique involves a direct study of the equations which describe the behavior of the system under consideration. It is particularly suited to processes for which the relevant differential equations, although known, are too difficult to solve. The general method of establishing similitude is to introduce non-dimensional quantities such as $\bar{P} = P/P_o$, $\bar{u} = u/u_\infty$, $\bar{x} = x/l$, etc. into the describing differential equations of the physical system. Certain similarity parameters such as Mach number, Reynolds number, etc. result. If these similarity parameters are made the same for both model and prototype, the non-dimensional describing equations will be identical for both and therefore will have identical solutions for the unknowns $\bar{\rho}$, $\bar{P}$, $\bar{T}$, etc. Hence measurements of $\bar{\rho}$, $\bar{P}$, etc. on a model can then be used to find ρ, P, etc. on the prototype.

For the description of the flow of a viscous, compressible fluid, with the assumptions of Newtonian, continuum fluid, the set of describing differential equations are as follows:

Continuity: $$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_j} = 0$$

Momentum: $$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ik}}{\partial x_k} + \rho f_i$$

Energy: $$\frac{\partial \rho J}{\partial t} + \frac{\partial \rho u_j J}{\partial x_j} = \frac{\partial P}{\partial t} + \frac{\partial}{\partial x_k}\left[u_j \tau_{jk} - q_k\right] + \rho f_i u_i$$

State: $$f(p, \rho, T) = 0$$

where: $$\tau_{ij} = \lambda \delta_{ij} \frac{\partial u_l}{\partial x_l} + \mu\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

$$q_j = -k \frac{\partial T}{\partial x_j}$$

These equations, along with physical boundary conditions, have been used to establish similitude for many flow problems (Ref. 36, 50, 61, 62 and 68). For air under conditions of flow where the perfect gas model is valid, the principle similitude parameters are found to be N_{Re}, M, N_{Pr}, γ, $\bar{\bar{\mu}}$, $\bar{\bar{C}}_p$, $\bar{\bar{k}}$, T_o/T_∞, u_{t_o}/l, and the same geometry (Ref. 36). The terms u_{t_o}/l and T_o/T_∞ serve to define reference values, and the parameters $\bar{\bar{\mu}}$, $\bar{\bar{C}}_p$, $\bar{\bar{k}}$ require that the variation of μ, C_p, k with temperature be of the same form for model and prototype. For steady-flow testing in air at moderate Mach numbers, the more important similitude parameters are N_{Re}, M and N_{Pr}.

For the problem at hand these parameters are not sufficient to establish complete similitude. In the range of velocities and densities of interest in this study, the real gas effects make the assumption of an ideal gas model invalid; and over portions of this range more critical rarefied gas effects may be encountered. The equations shown above are based upon continuum concepts, which do not apply at extremely high altitude conditions. Rarefied gas effects are characterized by the Knudsen number, or ratio of mean-free path l' to a characteristic dimension. If similarity is to be obtained with respect to rarefied gas effects, the Knudsen number must be an invariant parameter. The problem of rarefied gas effects on similitude has been discussed at length by Calligeros and Dugundji (Ref. 36) and by Hayes and Probstein (Ref. 50).

In view of the complex nature of low-density hypervelocity flow in diffusers, it is doubtful that complete similitude can be achieved between model and prototype tests. Because of this fact an attempt is made to examine the importance of various flow parameters. The Mach number is obviously important since it establishes the compressibility effects. Also previous investigations, as pointed out in the state-of-the-art discussion, indicate that Mach number is an influencing parameter on diffuser performance. Although the rarefied gas effects as expressed by the Knudsen number may become significant at the upper altitudes of interest, they need not be considered over a large portion of the flow regime. Geometric similitude is certainly important as has been illustrated by many investigations.

The important parameters for this flow problem, listed in order of decreasing importance, are geometric configuration, boundary layer effects (Reynolds number), test section model and support effects, compressibility effects (Mach number), real gas effects (dissociation-recombination), and rarefied gas effects (Knudsen number). A more detailed discussion of the boundary layer effects and real gas effects follows.

3.2 REAL GAS EFFECTS

The conditions of very high temperature, low-density flow which are encountered in the design of hypersonic, high altitude testing facilities provoke a variety of physical phenomena which are not accounted for by the classical ideal gas model of air. These processes, collectively termed real gas effects, include vibrational excitation of the molecules, molecular dissociation, atom recombination, and, at higher temperatures, ionization of the gas. Each of these aerothermochemical phenomena is excited at a different finite rate which depends on the local pressure and temperature; the analysis of problems involving these rates requires consideration of the details of the vibrational and chemical relaxation rates. The situation is somewhat simplified in that the details of the vibrational or chemical rate laws need not be considered when these rates are everywhere much greater than the convection or diffusion rates in the gas (thermodynamic equilibrium flow), or when they are very much smaller than the flow rates ("chemically forzen" flow). These two extremes of real gas chemical behavior bound the maximum extent to which the nonequilibrium effects can influence the various results of gas dynamic analysis.

Because of the interrelationship between the fluid flow and the internal rate processes, the detailed calculations of nonequilibrium flow are at best a difficult task. Even when rather drastic simplifying assumptions are introduced, numerical methods must be adopted. Calculations by such methods for the flow of air through a hypersonic nozzle have been made by Bray (Ref. 42) in England and by Hall and Russo (Ref. 69) in the United States. In both of these studies the flow is regarded as steady and one-dimensional, and transport and radiation effects are neglected. In both cases vibrational nonequilibrium is neglected, and the chemical nonequilibrium is restricted to a single dissociation-recombination reaction. The assumed details of the chemical model, however, differ somewhat between the two studies. More recently Vincenti (Ref. 4) has attempted to utilize a more complex gas model in extending the procedure used by Hall and Russo.

Bray, in order to simplify the situation as much as possible, takes the fluid to be a pure monatomic-diatomic gas and adopts approximate equations to describe the chemistry of the process. The vibrational energy of the diatomic species is taken equal at all times to one-half the fully excited value corresponding to the local temperature. Bray finds that, for appropriate values of the temperature and pressure in the reservoir, significant departures from chemical equilibrium can appear as the flow proceeds down the nozzle; and this result is true for a wide range of values of the chemical rate parameters. Furthermore, once an appreciable deviation from equilibrium appears, the chemistry of the flow becomes rapidly "frozen" and remains so the rest of the way down the nozzle.

Hall and Russo set up the equations for a somewhat more realistic model of air by considering a monatomic-diatomic gas in an inert diluent. The relations describing the chemistry are also less simplified than Bray's relations, and the vibrational energy is taken equal to the equilibrium values for a quantized harmonic-oscillator model at the local fluid temperature. Their calculations give results having the same general features as those of Bray.

Several other theoretical analyses have been reported (Ref. 19, 21, 52, 82, 83, 84, and 87) which investigate certain aspects of this problem. Kuo (Ref. 49) attempted to formulate the boundary-layer problem under the suppositions that the fluid in the main stream is a simple diatomic gas and that when dissociated, the resulting mixture is in dissociative equilibrium. Under these assumptions, the flow quantities such as surface temperature, skin friction coefficient and heat transfer coefficient are evaluated; and the effects of the transport coefficients dealing with viscosity, conductivity, and diffusion are examined. It is shown that under the condition of equilibrium dissociation the effects of dissociation on the transport coefficients are not large at very high speeds.

The conclusions of Bray and of Hall and Russo have been shown experimentally to be qualitatively correct by Wegener (Ref. 88) and Nagamatsu, Workman and Sheer (Ref. 14). Nagamatsu et. al. report that for reservoir pressures greater than 500 psia, the expansion of air in a conical nozzle is essentially in equilibrium for reservoir temperatures up to about 4500°K. For temperatures greater than 4000°K and pressures lower than 100 psia, the expanding air is almost frozen. At a given area ratio for the nozzle and a given reservoir pressure, the expansion process ramains in equilibrium up to a certain reservoir temperature; beyond this temperature the flow expansion deviates rapidly from the equilibrium process and approaches the frozen case.

It appears that no attempt has been made to analyze the real gas effects on diffuser design and performance. Since the diffuser section will necessarily be short in length in order to minimize boundary layer effects, it is logical to expect non-equilibrium flow to exist in a portion of the diffuser. No attempt is made here to make a detailed analysis of these effects but an attempt is made to show qualitatively some of the effects.

A one-dimensional flow model is assumed and the flow parameters are investigated for dissociated equilibrium as compared to an ideal gas model, (constant ratio of specific heats). The properties for dissociated equilibrium were obtained from the tables prepared by Goin (Ref. 43). In Figure 7 the effect of dissociation and recombination on the area required to pass the flow is shown. In this figure the area ratio A/A^* vs. Mach number is plotted for equilibrium dissociated flow from stagnation conditions of 10,000°K and 500 atm. Curves are also presented in this figure to illustrate the results which would be obtained by assuming the flow to behave with a constant ratio of specific heats ($\gamma = 1.3$ and $\gamma = 1.22$). It is noted that the real gas effects are sufficient to appreciably influence the area required and that a simple flow model will not suffice in designing a diffuser operating under these conditions.

The stagnation pressure ratio P_{o_y}/P_{o_x} vs. Mach number across a normal shock is plotted in Figure 8 for several values of γ = constant. Also plotted are points to indicate the real gas effects for several different stagnation states. The theoretical analyses of Bray and others show that the stagnation pressure ratio across shocks is only slightly influenced by frozen flow. The effect of pressure on the degree of dissociation can be noted in this figure by comparing stagnation pressure ratios for a given Mach number and different stagnation states (i. e., $M = 20$ for $T_o = 6000$°K, $p_o = 2000$ atm and $T_o = 6000$°K, $p_o = 100$ atm). It may be concluded that the analysis of a normal shock can be accomplished by using an ideal gas model, provided that a suitable value of γ is chosen, rather than using a complex model which takes into consideration real gas effects.

Figure 9 illustrates the real gas effects upon the isentropic pressure ratio for various Mach numbers. This flow characteristic for two different stagnation states is compared with that for two ideal gas models having different values of γ . As in the previous figure the influence of pressure upon the real gas effect is illustrated.

An "ideal" diffusion process is illustrated in Figures 10 and 11. These curves have been obtained by assuming isentropic flow from the test section to a normal shock. The ratio of static pressure downstream of the shock to test section static pressure as a function of shock Mach number has been plotted. In Figure 10 a test section simulation of $M = 22.77$ and 350,500 feet altitude is assumed, and in Figure 11 test section conditions of $M = 10.26$ and 107,900 feet are assumed. The results for dissociated equilibrium have been compared with those for γ = constant. Here again the deviations due to the real gas effects are shown to increase with increasing Mach number and altitude simulation. In Figure 12 the ratio of stagnation pressure downstream of a normal shock to the test section stagnation pressure for different shock Mach numbers is presented. The "ideal" diffusion process explained above was used to obtain the results illustrated here.

The real gas effects in diffuser flow should be less pronounced than in nozzle flow, since the increasing pressure will tend to increase particle collision frequency and thus decrease dissociation effects. Although a complete quantitative analysis of the real gas effects upon diffuser performance has not been made, it may be concluded that caution must be used in designing and analyzing diffusers for applications in hypervelocity low-density wind tunnels.

3.3 BOUNDARY LAYER EFFECTS

The performance of a diffuser is dominated by the behavior of the boundary layer. In the strong adverse pressure gradient which necessarily exists in a diffuser, the flow in the retarded layers undergoes a larger reduction of velocity than the rest of the flow, and the boundary layers have a tendency to grow thicker and possibly to become separated from the wall. This invariably occurs in a way which impairs the recompression, for the adjustment is such as to relieve the adverse pressure gradient. The kinetic energy diverted to the strong turbulent motion which results from nonuniformity of the flow and flow separation, is finally dissipated by friction and is therefore ineffective in producing pressure increases. It is not possible, with present knowledge, to treat these effects theoretically and thus to design the optimum diffuser. In the past the idealized one-dimensional treatment has been supplemented by empirically determined coefficients. Presently, Mickey (Ref. 29) is attempting to solve the complete Navier-Stokes equations for laminar low-density nozzle flow. If this effort proves successful the same approach could be utilized to study diffuser flow.

At low Reynolds numbers there is, in addition to the thick boundary layer formed on the diffuser walls, increased boundary layer type flow generated by the model in the test section. This interference effect of the model may have a strong influence on the performance of the diffuser. Lukasiewicz (Ref. 64) summarizes data which show that the model and support have an appreciable effect on diffuser performance even at high Reynolds numbers ($\sim 10^6$), and Professor Maslach (University of California, Berkeley - Ref. 72) related that their experience showed that the 30 or 40 percent pressure recovery over the test section static pressure at Mach numbers between 3 and 4 for their low-density tunnel was greatly reduced upon the insertion of a model. The experimental results of Potter (Ref. 38) also indicate a reduction in diffuser performance due to blockage in the test section.

Since the performance of a diffuser may be affected to a large extent by shock wave phenomena, it is instructive to review some of the qualitative effects which boundary layers have on shocks. The idealized one-dimensional treatment of shocks disregards the nonuniformities arising from the presence of the boundary layers; or more correctly it replaces, as an approximation, the nonuniform flow by a fictitious uniform mean flow. Actually, however, the central core of essentially uniform velocity is able to support larger pressure discontinuities than can be supported within the boundary layer, because of the higher Mach number of the core. Within the boundary layer the Mach number decreases as the wall is approached, and near the wall the velocity becomes subsonic and shocks are impossible. Thus, the simple mechanism of the normal shock is incompatible with the presence of boundary layers. Only for low supersonic velocities and thin boundary layers (high Reynolds number) is a quasi-normal shock possible in duct flow. Otherwise, a more complicated, non-one-dimensional pattern is produced, which, for sufficiently high Mach numbers, becomes multiple. Above a certain boundary layer thickness this multiple pattern will contain only oblique shocks crossing in the center of the stream and reflecting back and forth in the center supersonic region of flow, while the region adjacent to the wall is adjusted gradually to the pressure increase. Crocco (Ref. 79) states that the total entropy increase across such a reflected wave phenomena must be nearly the same as in a normal shock. However, in the reflected wave phenomena region only a part of this entropy increase is produced by the actual shock waves, and the rest is due to the dissipative processes present in the strongly turbulent regions adjacent to the walls. In fact, it may well be that the total entropy increase due to the system of oblique shocks of small strength constituting the shock pattern, is only a small fraction of the total entropy rise, in which case the predominant cause for the entropy increase resides in the dissipative turbulent regions. This observation indicates the critical influence which boundary layer flow will have on diffuser pressure recovery, since greater entropy increases are indicative of lower stagnation pressure recovery for adabatic flow.

It has been shown by Lukasiewicz (Ref. 64) and Shapiro (Ref. 90) that the performance of shock diffusers may be improved by providing a sufficient length of constant area duct or throat in which the shock system causes a pressure rise. Experimental data shows (Ref. 90) that the overall rise in pressure through the shock system (multi-reflections) is essentially the same as for the idealized normal discontinuity. As the Reynolds number is decreased, the gain in recovery pressure from such constant area sections will probably be smaller because of the very large viscous dissipation.

An analysis based upon the method of McLafferty (Ref. 65) has been made to indicate quantitatively the effects of boundary layer thickness upon pressure recovery through a "normal" shock with boundary layer flow upstream. The results of the analysis are presented in Figures 13 and 14 for a 1/7 - power law turbulent boundary-layer profile approaching the shock and a uniform profile downstream of the shock. In Figure 13 the theoretical pressure recovery (indicated by stagnation pressure ratio) is plotted as a function of the ratio of displacement thickness of the boundary layer to the semi-height of the flow passage for different values of midstream approaching Mach number. In Figure 14 the ratio of pressure recovery with boundary layer to pressure recovery (normal shock recovery) without boundary layer is plotted as a function of displacement thickness. This curve is essentially independent of approach Mach number. Both of these figures are based on a constant ratio of specific heats of 1.4.

Since the range of Reynolds numbers of interest in this investigation is from approximately 10^4 to 10, there will necessarily be extensive boundary layer type flow in the diffuser; and it is believed that this will be the predominant factor in determining diffuser performance. In Part 4, specific experimental tests will be recommended to evaluate more exactly the boundary layer effect on diffuser performance.

4.0 EXPERIMENTAL TEST

This investigation has clearly indicated the lack of information pertaining to wind tunnel diffuser performance for the range of application outlined in Part I. Some of the difficulties involved in making a conclusive analysis have been noted, and it appears that a series of experimental investigations is required to overcome these difficulties. It is believed that the results of this experimental endeavor could be utilized to predict with some degree of confidence diffuser performance in the range of application previously stated.

At the present time, facilities do not exist which can duplicate both geometric scale and flow conditions of interest; consequently, it becomes necessary to simulate the desired test conditions. Simulation is the technique of duplicating only the dimensionless parameters most intimately associated with and governing the phenomenon being studied. For example, in boundary layer flows Reynolds number is generally of prime importance, whereas for compressibility effects the Mach number is usually the important factor. The dimensionless parameters which appear to be important for the diffuser flow problem have been discussed in Part II. Although Mach number, Reynolds number, and Knudsen number characterize three important aspects of the problem, no single parameter characterizes the real gas effects. Of no less importance is the geometric configuration, which cannot be characterized by a single parameter either.

Due to the interdependence of the various flow parameters it is impossible to obtain complete similarity between a model test and the actual application. In order to have complete simulation the actual configuration and flow conditions would have to be tested. Past experiences indicate that much can be gained from experimental test even though complete simulation is not obtained. Thus, while no single facility exists which can duplicate all of the important parameters, it appears feasible to utilize existing facilities to gain valuable information on diffuser performance by simulating one or two parameters at a time. Each parameter or effect will be discussed separately and suggestions given concerning the type of tests and range of flow parameters to be investigated.

The most important effect is that of the boundary-layer flow. In general, this type of effect has been characterized by the Reynolds number, but could possibly be characterized better by the ratio of boundary layer thickness to the semi-height or radius of the flow passage. It has been pointed out in Part II that diffuser performance for Reynolds numbers of approximately 10^7 per foot has been rather throughly investigated (Ref. 55, 64, and 66), but only one investigation has been conducted at appreciably lower Reynolds numbers (Ref. 38). There is an acute need for diffuser performance data for Reynolds numbers between 10^4 and 10. The results of Potter (Ref. 38) were obtained at a Reynolds number per foot of approximately 2640. If lower Reynolds numbers cannot be achieved in existing facilities it would be very enlighting to obtain performance data for flow at higher values but less than 10^5. A wide variation in Reynolds number can be obtained, even with a limited stagnation pressure capability, by controlling the degree of flow expansion. In general, it is necessary to operate at high stagnation pressure to avoid or minimize thermo-chemical nonequilibrium. It appears that the best way to obtain a wide range of Reynolds numbers in hypersonic flows is to operate at high stagnation pressure and to vary the stagnation temperature and flow Mach number. Thus, high Reynolds numbers can be obtained with a low stagnation temperature and low Mach number, and low Reynolds numbers with high stagnation temperatures and high flow Mach numbers.

Probably the second most important parameter is the geometric configuration. This parameter becomes increasingly important as the boundary layer type flow increases (low Reynolds numbers). The geometric consideration for high N_{Re} has been well summarized (Ref. 64, 66, and 55) by many investigators, but very little information is available at low N_{Re}. Due to the limited variety of geometric configurations tested, only a few conclusive facts on geometry effects were presented by Potter (Ref. 38). These facts have been presented in Part II and only the additional geometric aspects will be discussed here. The angle of convergence and the length of the entrance part of the diffuser may have an important effect on the performance. The diffuser throat area is also an important variable. It would be most desirable to utilize a variable configuration type diffuser or an extensive collection of fixed geometry diffusers in a series of experimental tests to establish the influence of geometry on performance for low Reynolds numbers.

It is noted in Figure 3 that the mean free path or distance between particle collisions is of the order of 20 feet for simulation of an altitude of 400,000 feet. Thus, it is anticipated that rarefied gas or noncontinuum flow effects will become significant for higher altitude flow simulation. The Knudsen number, which is the ratio of the mean free path to a characteristic dimension, is used to identify noncontinuum flow regions. It is estimated that the mean free path in Potter's test (Ref. 38) was approximately 10^{-2} feet. If the 4.5-inch diffuser entrance radius were chosen as the characteristic dimension, the Knudsen number would be approximately 2×10^{-2}. For flow where boundary layer effects are important, the Knudsen number is taken as a function of Mach number and Reynolds number. It would appear that the data obtained by Potter were in the region of slip or transitional flow, which occurs between true continuum flow and free molecule flow. For the range of altitudes and velocities of interest it is probable that free molecular flow may exist in portions of the diffuser. Experimental data between $M/\sqrt{N_{Re}} = 10^{-2}$ and $M/N_{Re} = 3$ could supply valuable information about the rarefied gas effects. The above criterion could be used, but Knudsen numbers based on ratio of mean free path to diffuser entrance radius would probably be more informative. If the latter parameter is used the range of investigation should be $10^{-3} < N_{Ku} < 60$. Obviously a variation of Knudsen number can be accomplished by changing either the magnitude of the characteristic dimension or the mean free path. The mean free path can be altered by varying the density.

The compressibility as expressed by the Mach number will be an influencing parameter, and an effort should be made to obtain data over a range of Mach numbers. Mach numbers between 10 and 30 are of interest, but the work of Johnston and Witcofski (Ref. 55) has supplied information at a Mach number of 20; thus, it appears that the influence of Mach number is somewhat better known than the influence of many of the other describing parameters. It should demand the smallest amount of investigation of all the describing parameters.

The real gas effects, as dictated by the thermo-chemical state of the gas, may be quite important in the range of application. The extent of the effects will be determined by the stagnation temperature and pressure, flow stream static pressure, and the residence time of a particle in the flow system. It has been pointed out in Part II that both analytical and experimental investigations indicate that dissociation-recombination and thermal state variations may appreciably effect the design and performance of the diffuser. For the flow to be in thermo-chemical equilibrium, rapid adjustment in both chemical composition and energy levels of the vibrational, rotational, and translational degrees of freedom is required. The adjustment may lag to such an extent that the fluid may be considered effectively frozen insofar as its thermodynamic adjustments are concerned. It is desirable to gather experimental information on both thermo-chemical equilibrium and frozen flow effects on performance. These data should be obtained for flow simulations of $M > 10$ and altitudes $> 200,000$ feet.

It must be realized that all of the objectives set forth cannot be obtained with existing facilities, but this is not new in developmental engineering. Since it is realized that limited time and facilities will not permit a complete study of this problem, the tests which are suggested are listed in the order of decreasing importance. Since it is possible to perform evaluations of more than one parameter in a single test, some tests will include the study of more than one primary parameter. The following experimental investigations are recommended:

I. Boundary Layer and Geometry Effects.

These effects are grouped together because both may be investigated simultaneously. The optimum geometric configuration of the diffuser (the convergent angle and length, throat area and length, and the divergent angle and length) should be determined for as wide a range of Reynolds numbers as possible (values of N_{Re} from 10 to 10^4 would be desirable).

II. Rarefied Gas or Noncontinuum Flow Effects.

The effects of the type of flow or flow regime (continuum flow of slip flow) on diffuser performance should be determined. For a Knudsen number based on the mean free path and the diffuser entrance radius, a range from 10^{-3} to 60 will give sufficient information.

III. Real Gas Effects.

This investigation should establish the conditions which determine whether the fluid flowing through diffusers is in equilibrium or may be cons: ·red frozen, and should determine the degree to which equilibrium or the lack of equilibrium influences the pressure recovery. These effects will be encountered for flow simulation requiring stagnation temperatures greater than 4000°K and stagnation pressures less than 500 psia.

In view of the interrelationship among the various flow parameters, it is possible that the information obtained from experimental investigation I may substantially reduce the amount of testing required in II and III. Careful evaluation of all flow parameters should be made during all tests in order to obtain the largest amount of useful information from the smallest number of tests.

5.0 CONCLUDING REMARKS

The exhauster or pumping system requirements for a low-density hypervelocity wind tunnel are altered considerably depending upon whether no pressure recovery or even one percent of normal shock recovery is obtained with a diffuser. Therefore, the rather low recovery ($< 10\%$) which appears likely for these diffusers may be just as impressive as the 100-200 percent recovery for high Reynolds number - low Mach number facilities.

The results of this investigation are inconclusive insofar as predicting recovery values as a function of Reynolds and Mach numbers. However, it is apparent that some recovery can be expected even under the most unfavorable conditions, and the results from the recommended tests should supply sufficient information to indicate the magnitude of this recovery. Also it appears conceivable that less conventional methods, such as boundary-layer removal by suction or cryopumping, or shaping the fluid stream by magneto-hydrodynamic means, might prove feasible. It appears that the container walls will be the primary source of boundary-layer type flow; thus, if these wall effects could be eliminated some significant dividend might be achieved.

A theoretical study of diffuser performance should be undertaken and the several possible approaches should be carefully analyzed. In order to determine the validity of a theoretical analysis, additional experimental information on diffuser performance is needed. The tests to provide this information are those recommended in Part IV of this report. In order to formulate certain aspects of a complete theoretical analysis, a better understanding of the region of flow which lies between continuum flow and free molecular flow is necessary. It is therefore recommended that a basic experimental research program be considered which would study rarefied gas flow through constant area and varying area passages in this transitional flow regime.

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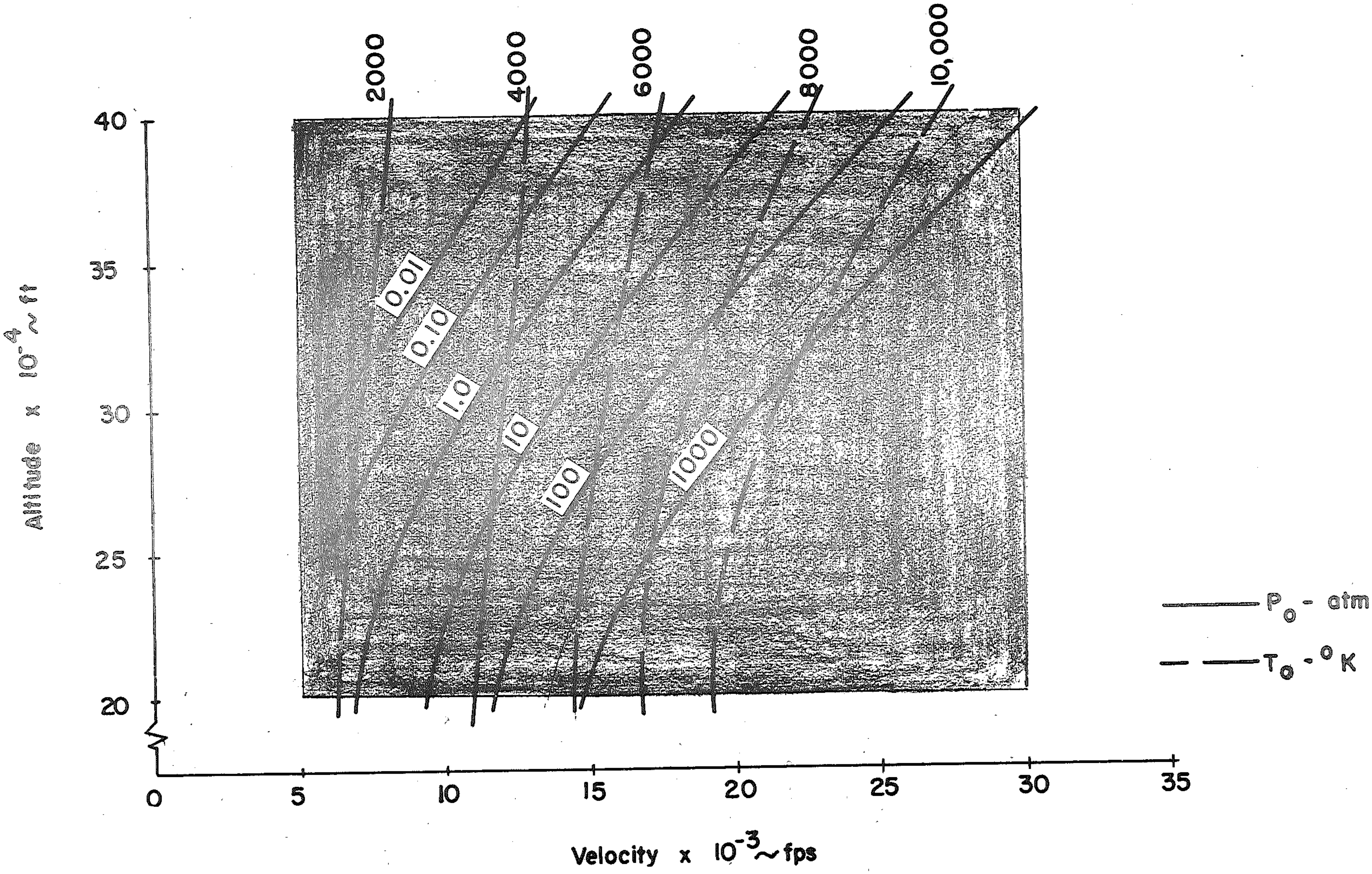

Fig. 1 Isentropic Stagnation Conditions for Equilibrium Air

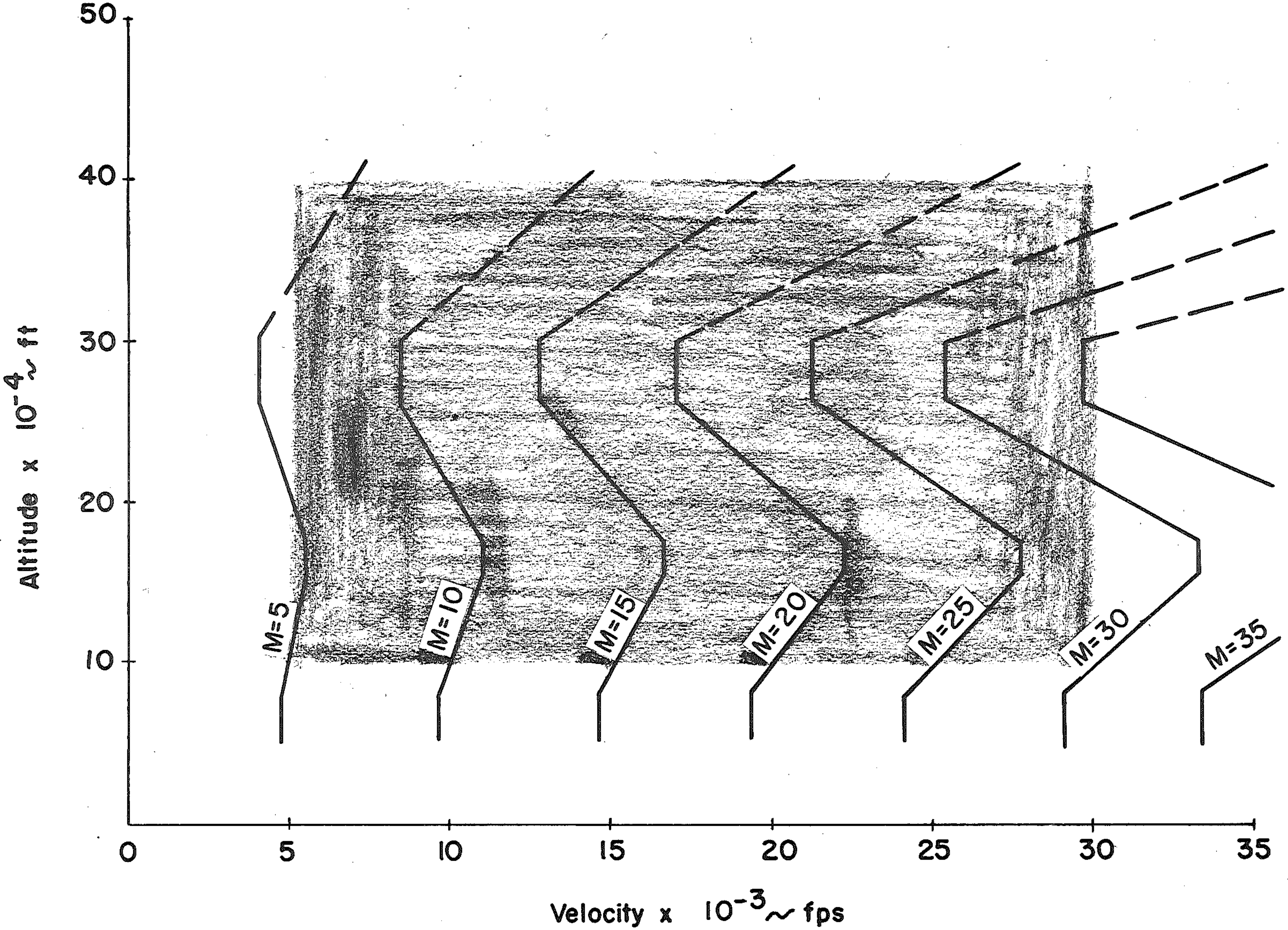

Fig. 2 Mach Number Range

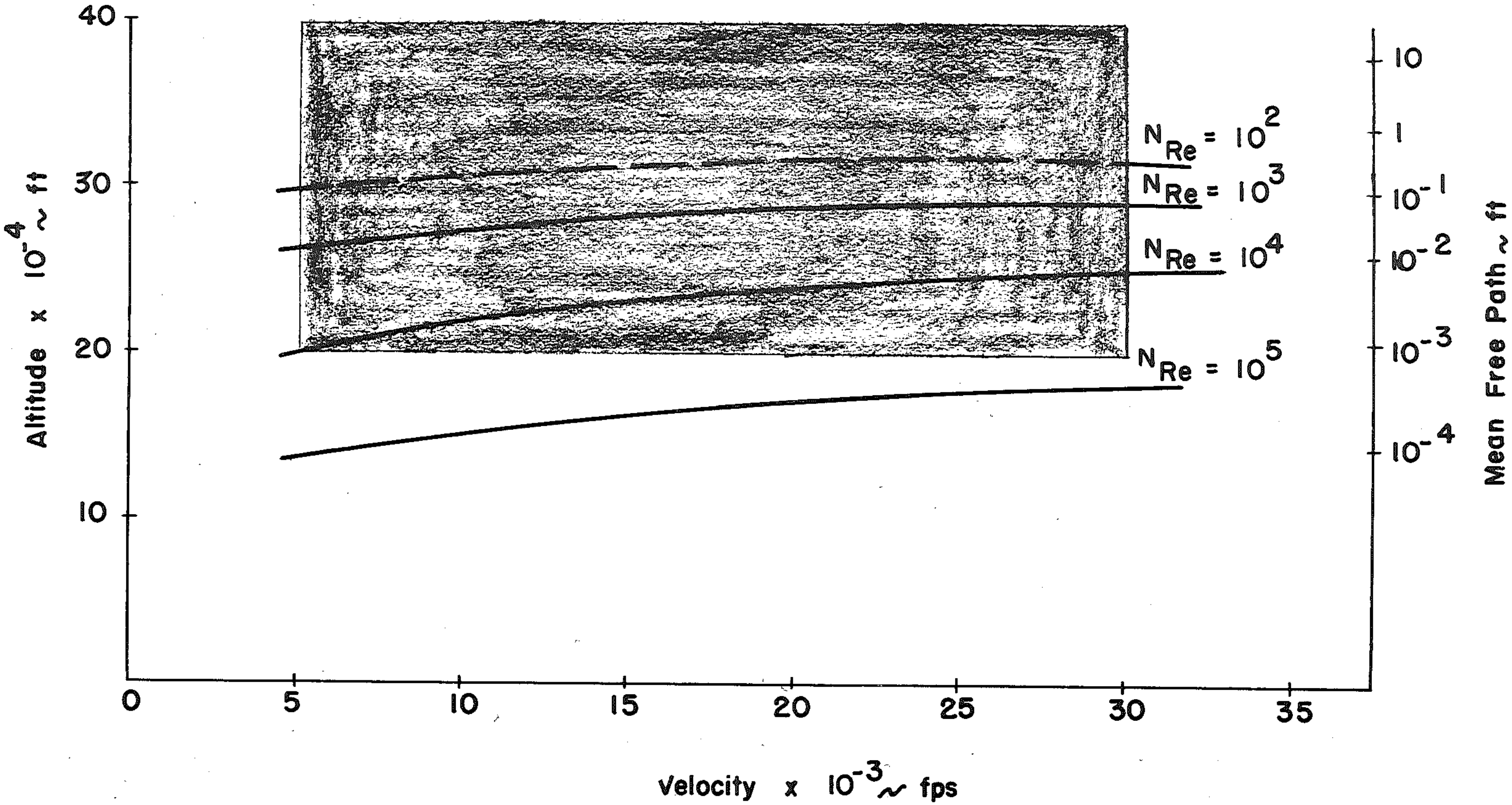

Fig. 3 Reynolds Number Range

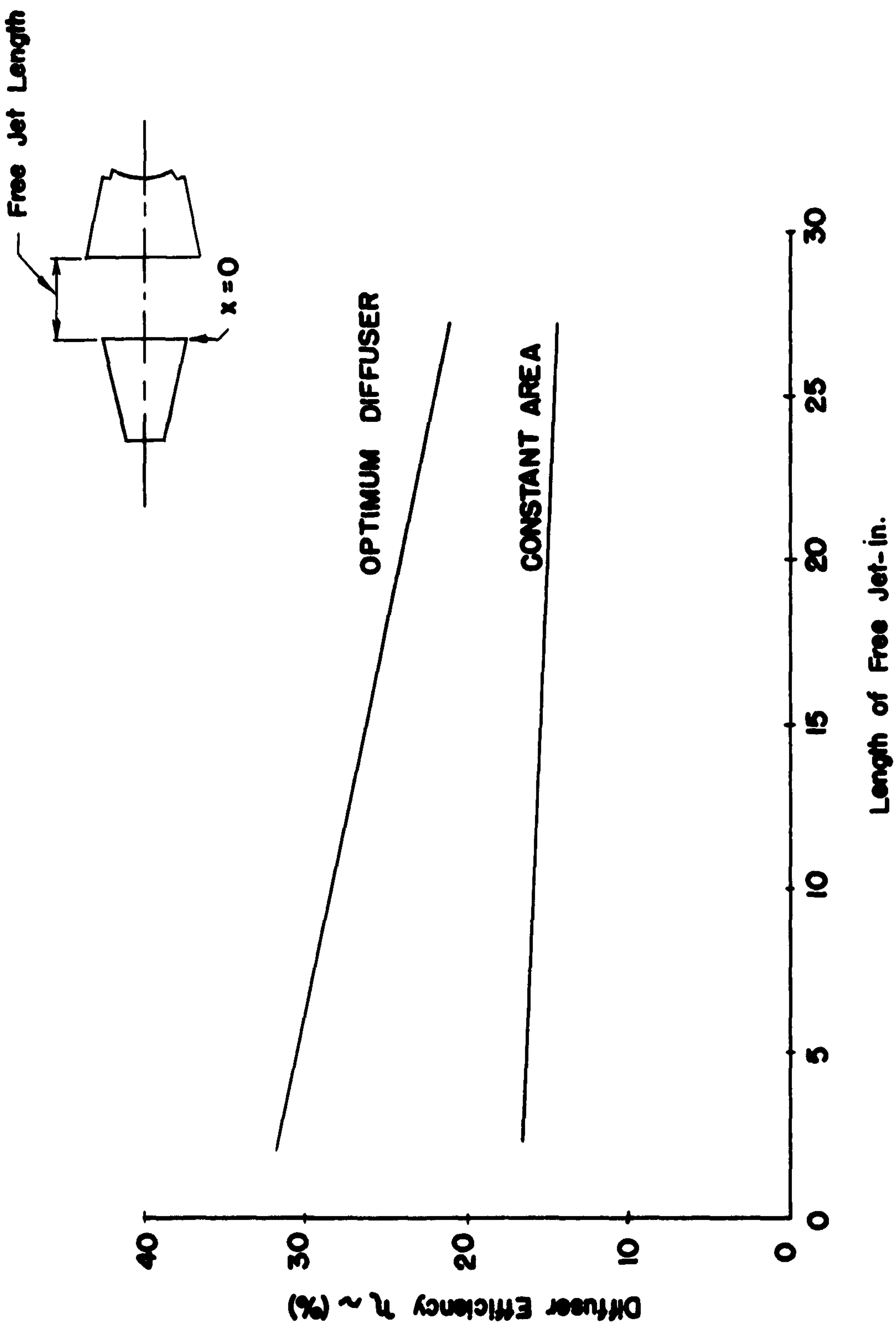

Fig. 4 Low-Density Diffuser Performance (Refs. 38 and 89)

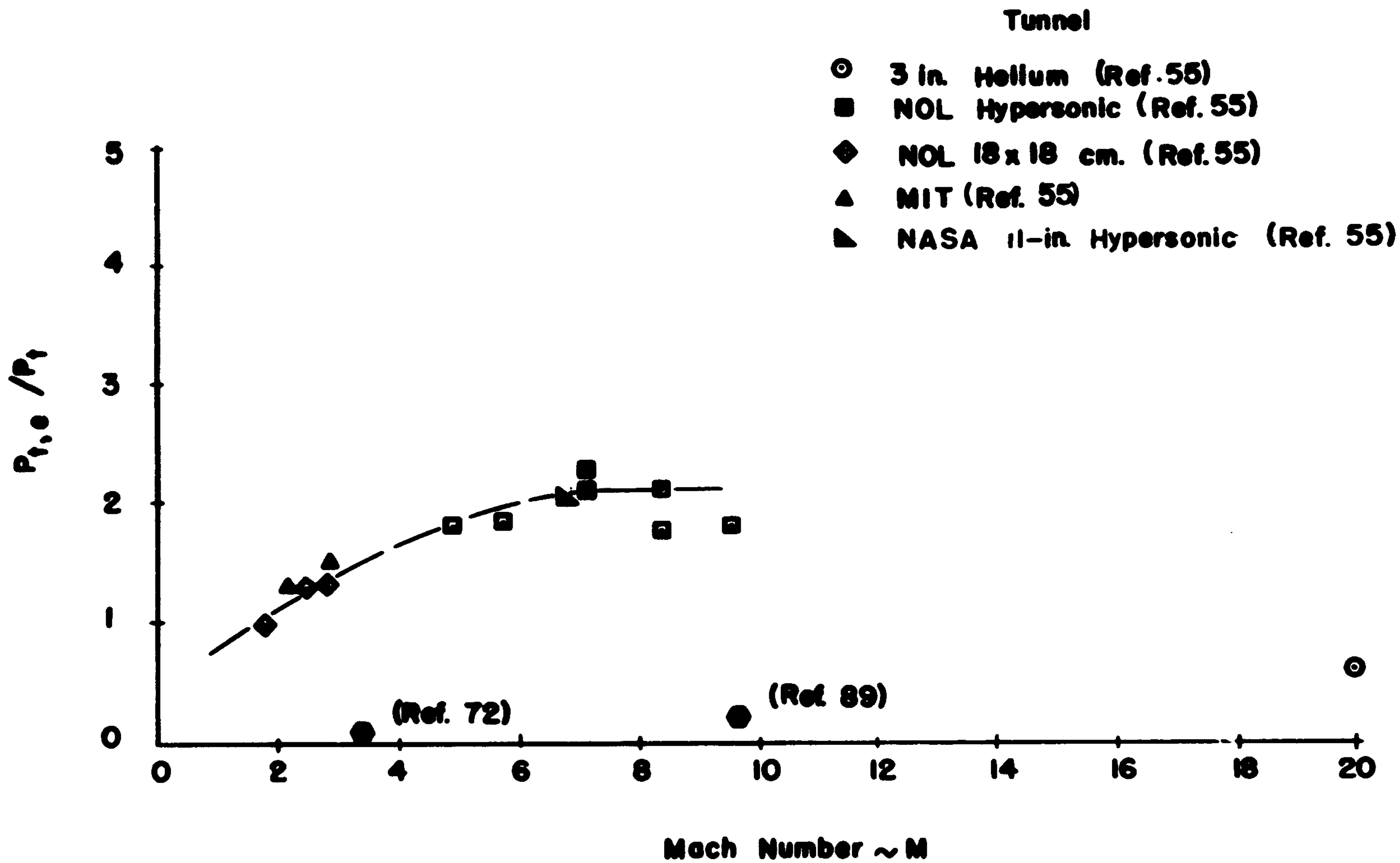

Fig. 5 Diffuser Pressure Recovery Performance

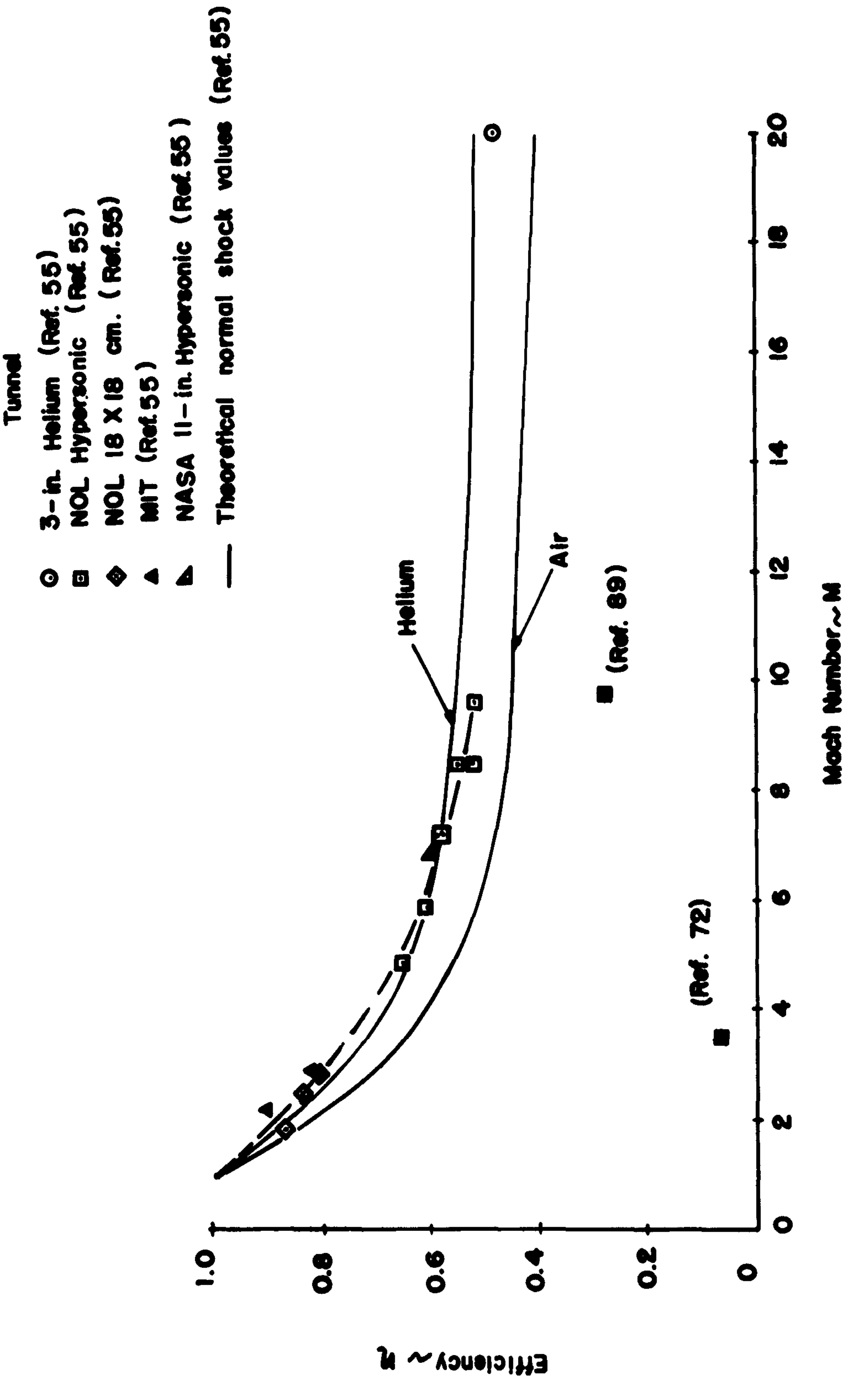

Fig. 6 Diffuser Efficiency vs Mach Number

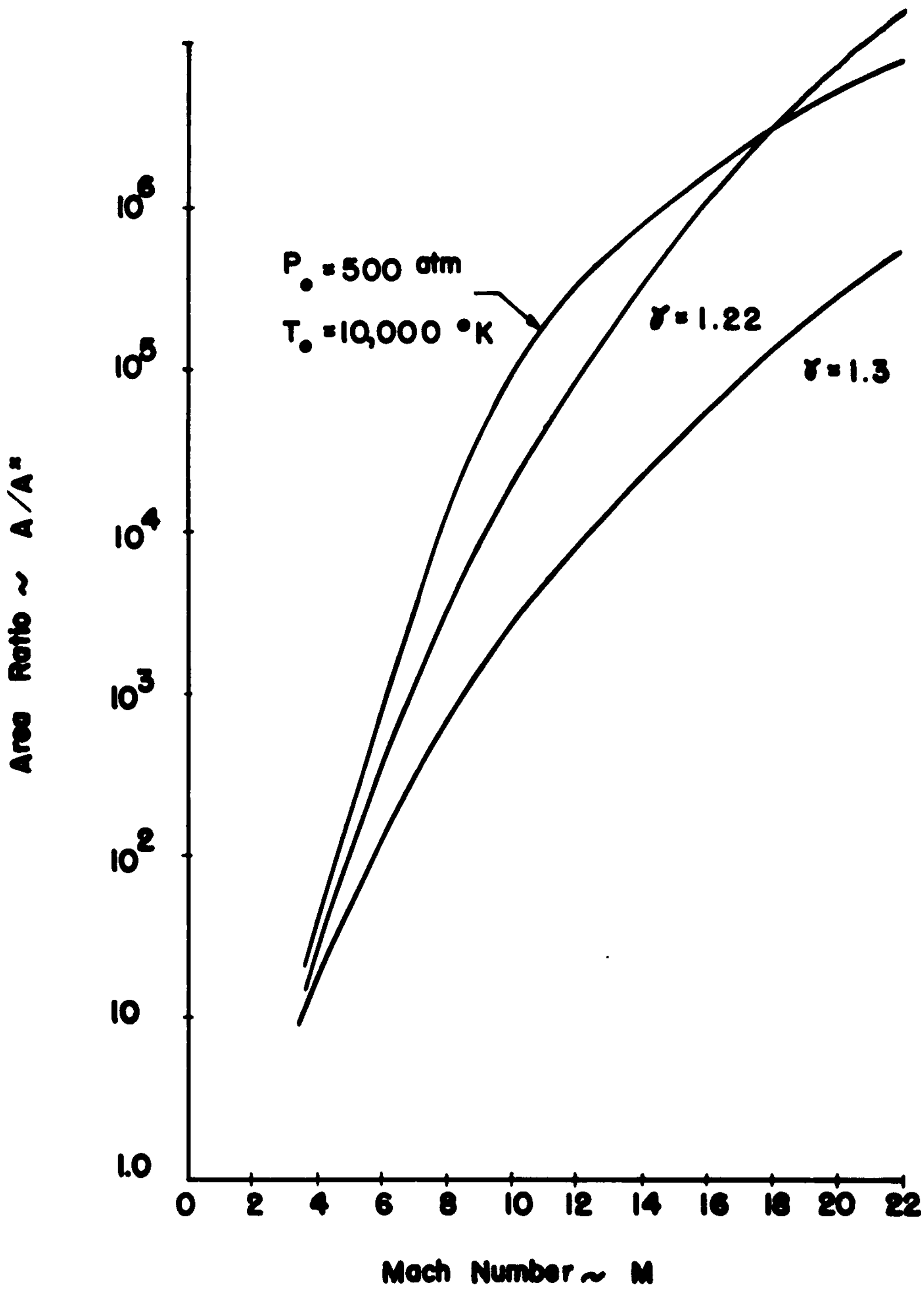

Fig. 7 Real Gas Effects on Area Ratio Requirements

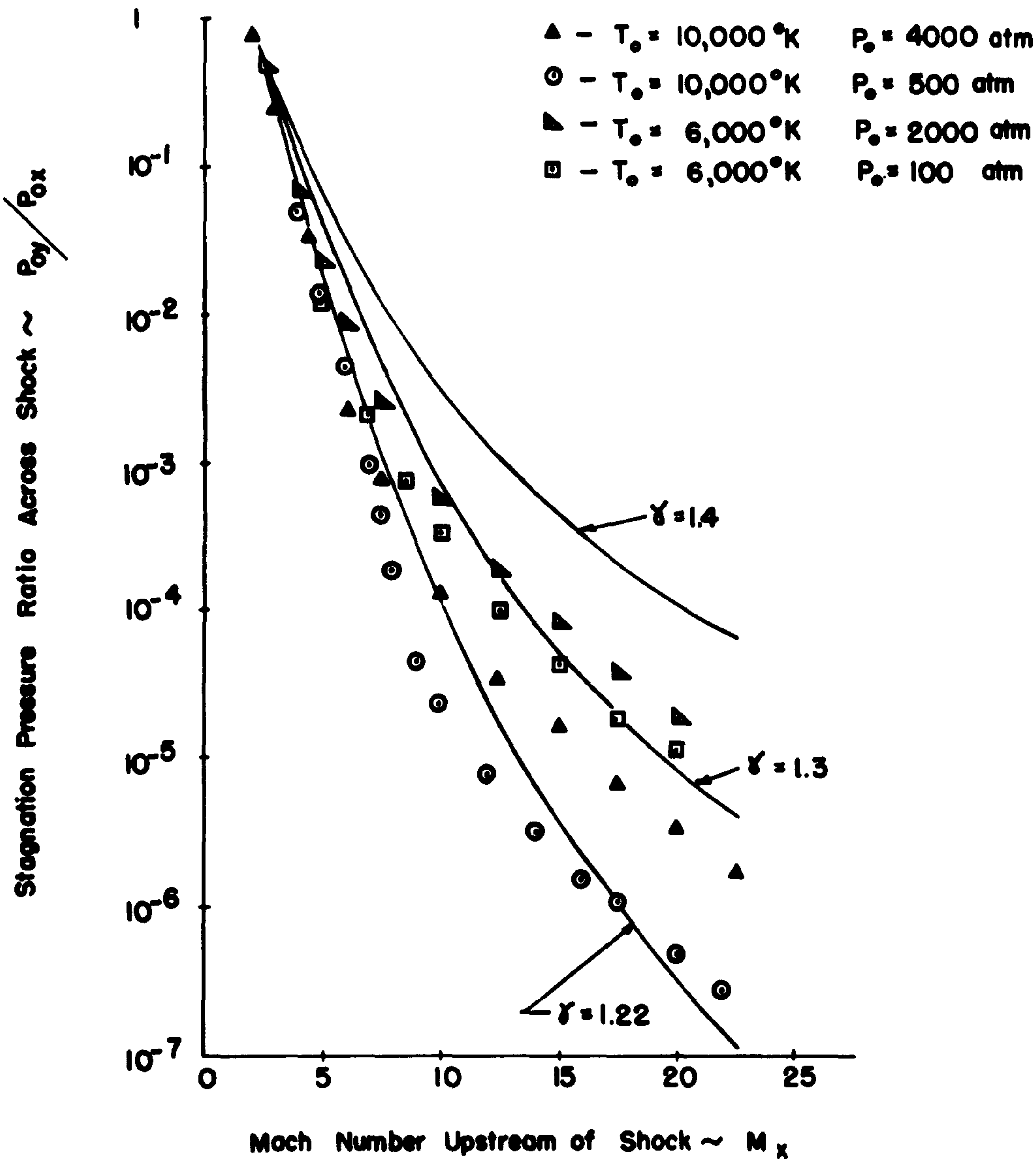

Fig. 8 Real Gas Effect on Stagnation Pressure Ratio across Normal Shocks

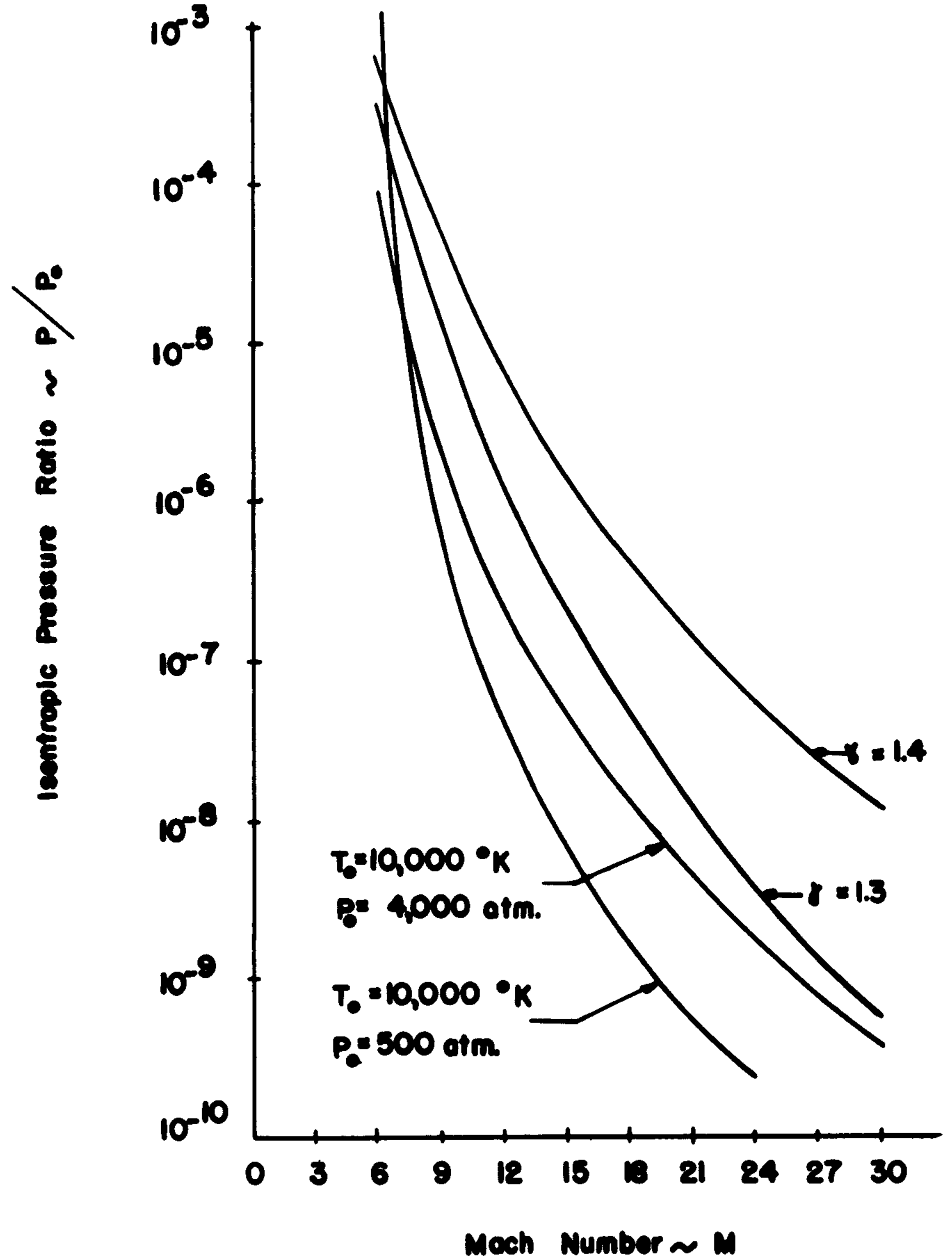

Fig. 9 Real Gas Effect on Isentropic Pressure Ratio

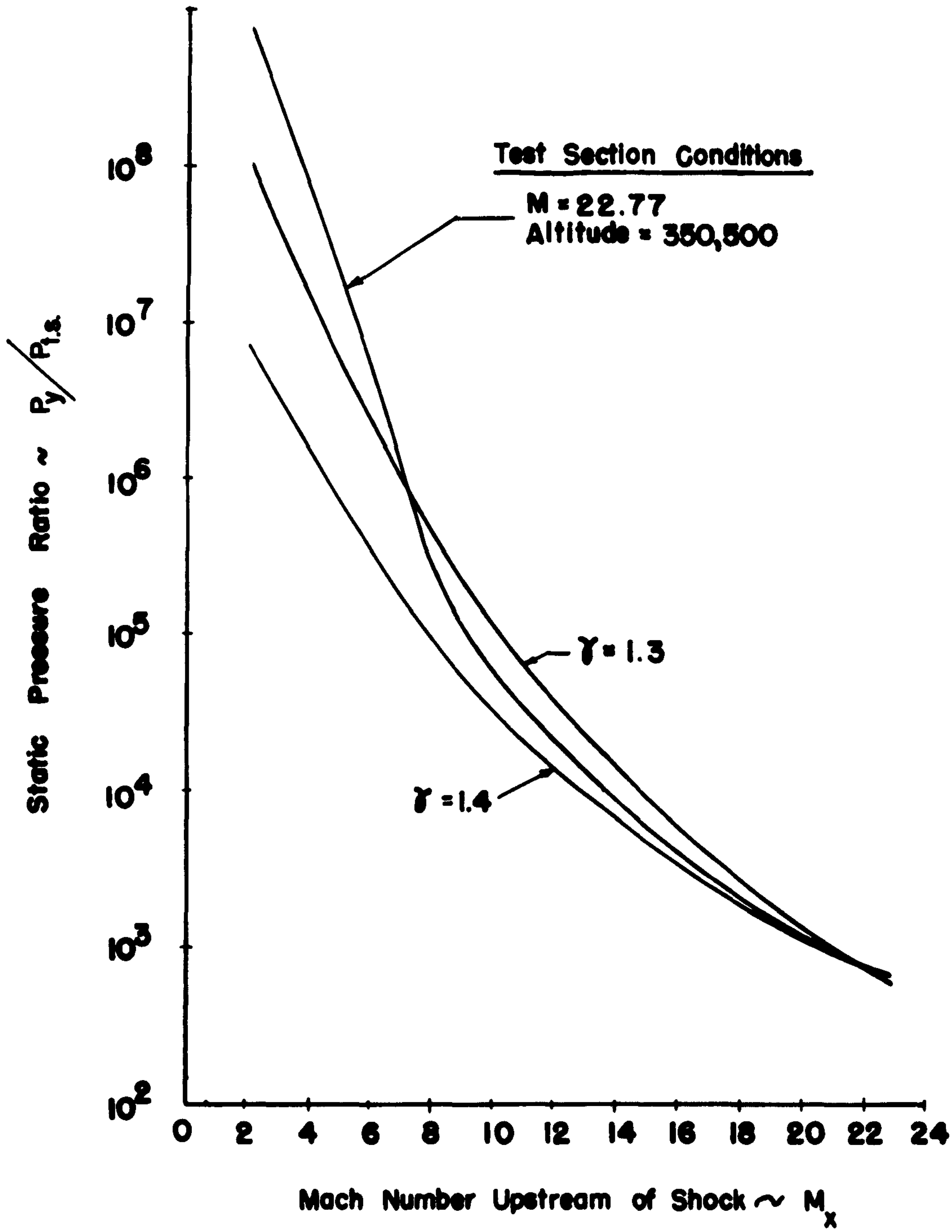

Fig. 10 Real Gas Effect on Static Pressure Ratio for Various Shock Mach Numbers

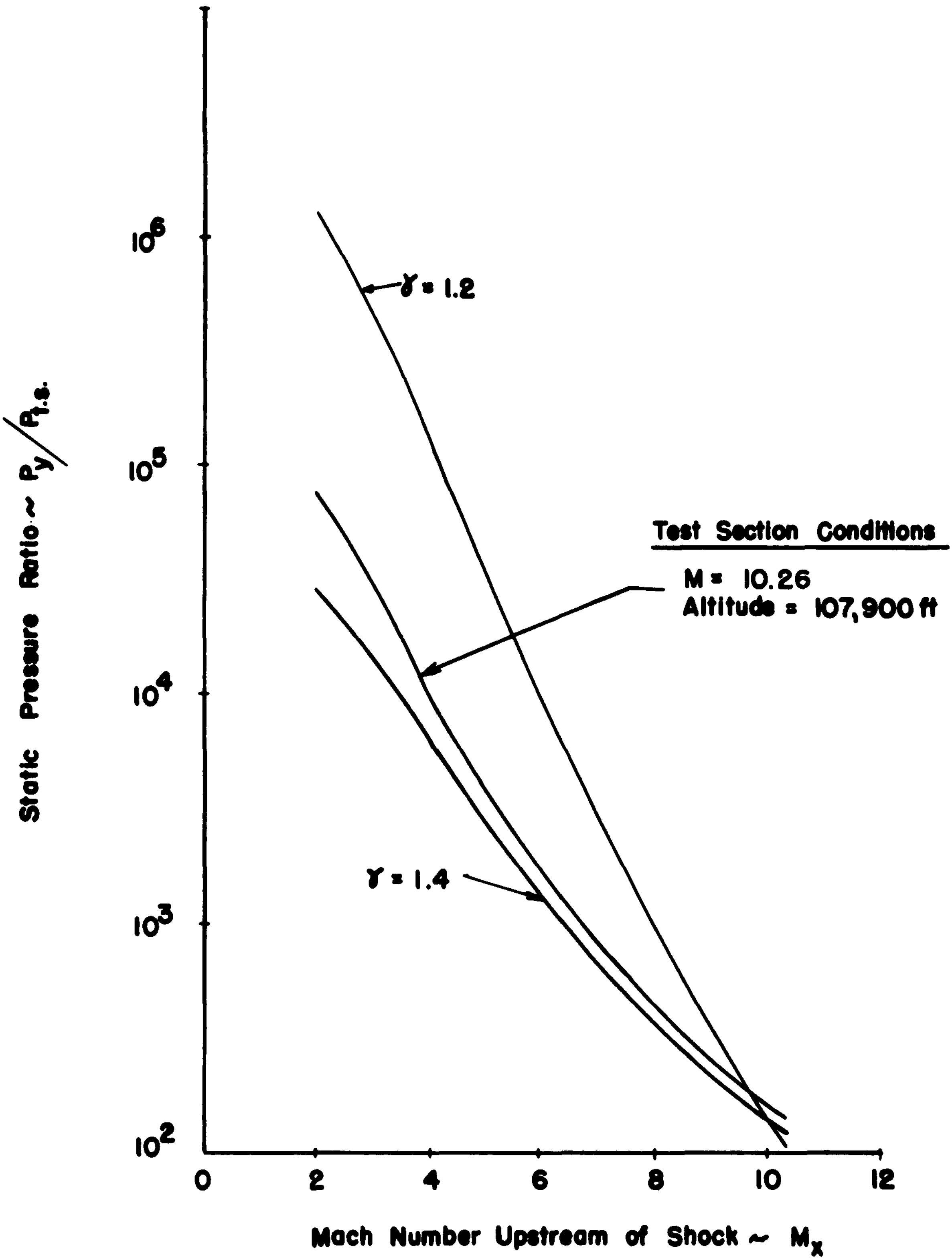

Fig. 11 Real Gas Effect on Static Pressure Ratio for Various Shock Mach Numbers

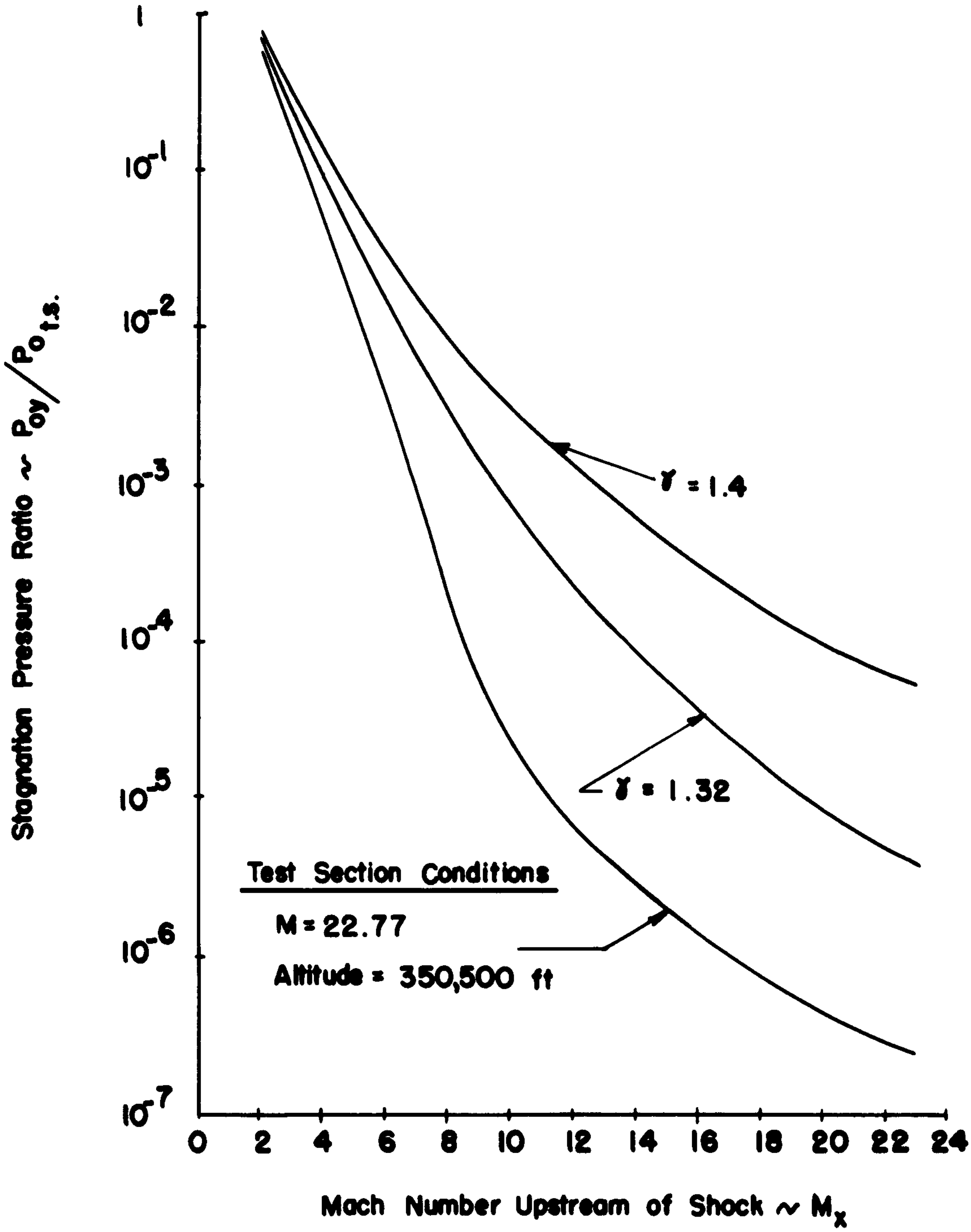

Fig. 12 Real Gas Effect on Stagnation Pressure Ratio for Various Shock Mach Numbers

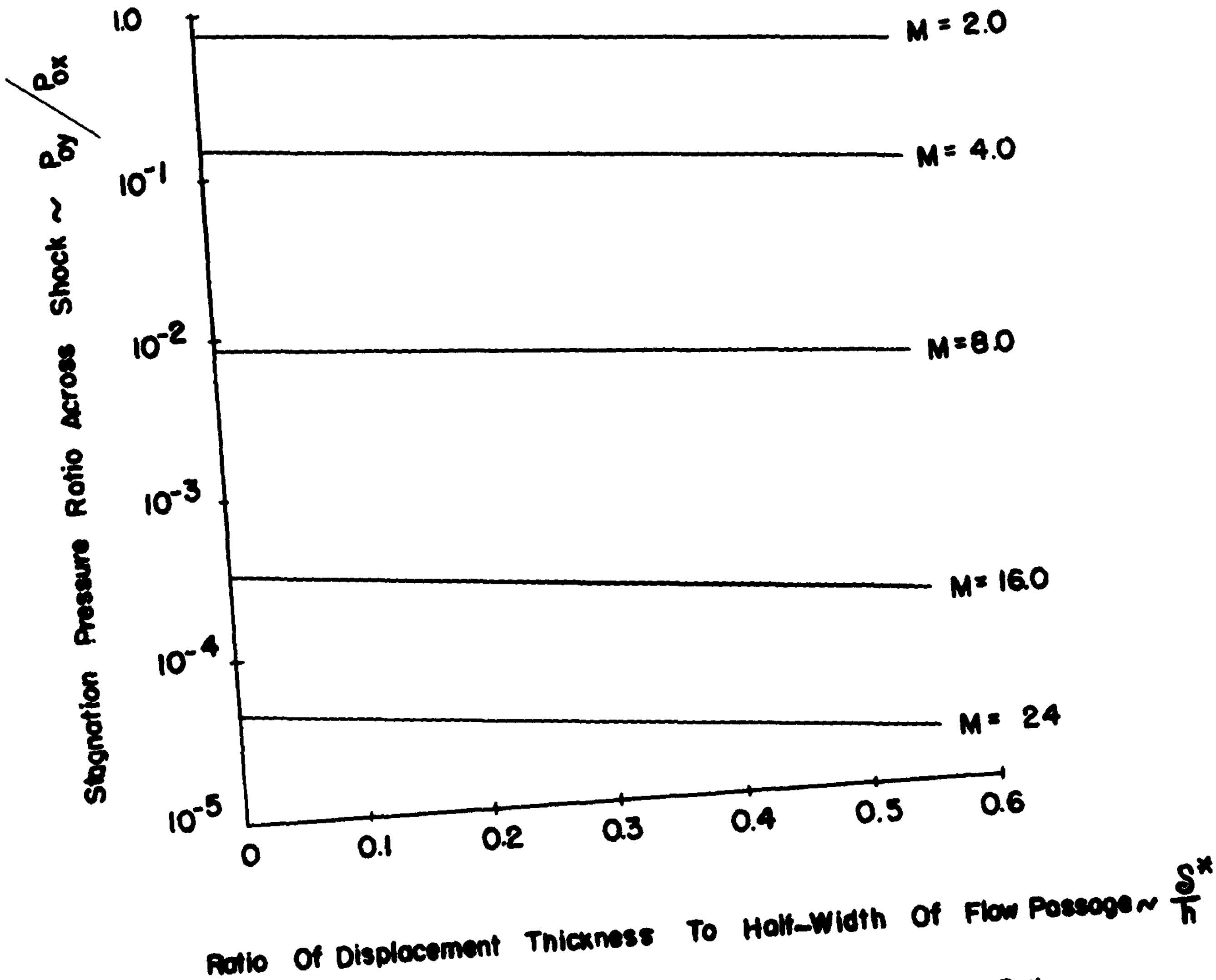

Fig. 13 Boundary Layer Thickness Effect on Stagnation Pressure Ratio

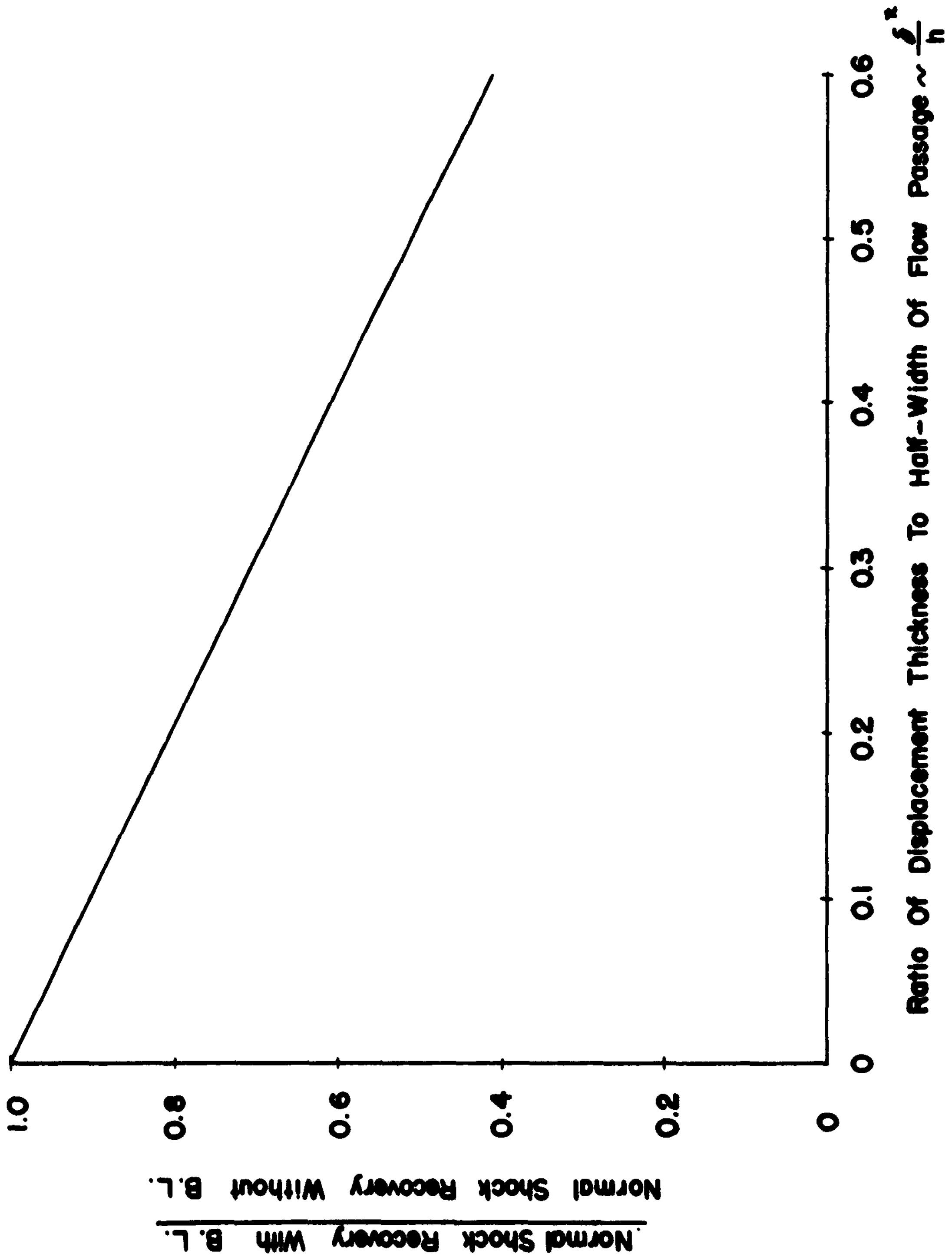

Fig. 14 Percent of One-Dimensional Pressure Recovery for Shocks in Boundary Layer Flow